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Isolating the Components of Intelligence

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In a recent volume (Intelligence, Information Processing, and Analogical Reasoning: The Componential Analysis of Human Abilities, 1977), ~~I~~ proposed a method called 'componential analysis' that provides a means to isolate the components of intelligent performance. The method was described in detail, and then tested in a series of experiments. But an important question was left unanswered by this early work: ~~Is~~ whether componential analysis generalizable to tasks other than analogies? More recently, ~~I have been~~ (over)

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investigating the generalization of the methodology to other tasks, and has have also been engaged in extending the methodology in order to increase its flexibility of application. The present article (a) briefly summarizes the structure of a componential analysis; (b) describes the method of precueing, the method originally used for isolating the components of intelligence; and (c) describes new methods that have also been successful in isolating these components in a variety of reasoning tasks.

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ISOLATING THE COMPONENTS OF INTELLIGENCE

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Running Head: Components of Intelligence

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Intelligence, in press

ISOLATING THE COMPONENTS OF INTELLIGENCE

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Informed educational and social policy decisions require identification and isolation of the components of intelligence. Recent declines in scores on college admissions tests, for example, have aroused concern over current instructional procedures and policies. A blue ribbon panel set out to discover just why scores have declined. But true understanding of why scores have declined requires understanding of just what it is that has declined, and this understanding requires in turn the isolation of the components that constitute what we believe to be intelligent performance.

In a recent volume (Sternberg, 1977b), I have proposed a method called componential analysis that provides a means to isolate the components of intelligent performance. The method was described in detail, and then tested in a series of experiments on reasoning by analogy. The experiments showed the success of the method in isolating components of analogical reasoning. But an important question was left unanswered by this early work: Is componential analysis generalizable to tasks other than analogies? During the past two to three years, I have been investigating the generalization of the methodology to other tasks, and have also been engaged in extending the methodology in order to increase its flexibility of application. I remain convinced that the set of procedures constituting componential analysis is indeed general, and that it is applicable to a wide range of problems requiring intelligent performance. I would like to present here a synopsis of some of these investigations, concentrating on how componential methodology is used to isolate the components of intelligence. I will first summarize briefly the structure of a componential analysis. Then I will describe the method of precueing, the method I originally used for isolating the components of intelligence. Finally, I will describe new methods I have used that have also been successful in isolating these components.

Structure of Componential Analysis

In its barest outline, a componential analysis consists of a series of intensive task analyses that, in combination, form the basis for an extensive task analysis. An *intensive task analysis* is an attempt to understand as fully as possible the psychology of a single task. An *extensive task analysis* is an attempt to integrate the findings from a series of intensive task analyses that together analyze some domain of tasks (e.g., analogical reasoning, deductive reasoning, perceptual speed, recognition memory). We shall concern ourselves here only with intensive task analysis.

Each intensive analysis consists of two parts, internal validation and external validation. *Internal validation* is an attempt to decompose global task performance into underlying component processes. *External validation* is an attempt to relate the identified components of task performance to individual differences in performance on external tasks. We shall concern ourselves here only with internal validation. Further details on the structure of componential analysis can be found in Sternberg (1977b, 1978).

The Original Precueing Method of Task Decomposition

In the original method of precueing (Sternberg, 1977b), the first step in a componential analysis was to form interval scores from the decomposition of the global task into a series of subtasks, as was done by Johnson (1960) in his pioneering method of serial analysis. Each _interval score_ is a score on one of the series of subtasks, and measures performance on a subset of the information-processing components required by the total task. Each subtask in the series of subtasks requires successively less information processing, and hence should involve reduced processing time and difficulty.

Analogies. Consider as an example an analogy of the kind used in my earliest componential experiments (Sternberg, 1977a, 1977b): "Four score and seven years ago" : Lincoln :: "I'm not a crook" : (a) Nixon, (b) Capone. In order to decompose the task, one can eliminate from the subject's information processing successive terms of the analogy. Since the analogy has five terms, up to five subtasks can be formed, although there seems to be no good reason for splitting up the two answer options. Consider, then, four subtasks. In each case, we divide presentation trials into two parts. In the first part, the experimenter presents the subject with some amount of precueing to facilitate solution of the analogy. In the second part, that of primary interest, the experimenter presents the full analogy. Solution of the analogy, however, is assumed to require merely a subset of the full set of components (that is, to be a subtask of the full task), because the experimenter assumes that the subject utilized the precueing presented in the first part of the trial to reduce his or her processing load in the second part of the trial. In the description of task decomposition that follows, it will be assumed that the analogies are presented either tachistoscopically or via computer terminal.

In the first subtask (which is identical to the full task), the subject is presented with a blank field (no precueing) in the first part of the trial. The subject indicates when he or she is ready to proceed, and then the full analogy appears. The subject solves the analogy, and then presses a button indicating a response of (a) or (b). In the second subtask, the subject receives a large subset of the task. The first part of the trial consists merely of precueing with the first term of the analogy. The subject presses a button to indicate that this term has been processed, and then the whole analogy appears on the screen. The subject solves it, and then indicates his or her response. Note that although the full analogy was presented in the second part of the trial, only the last four terms needed to be processed, since the first term had been preprocessed during precueing. The third subtask involves a smaller subset of the task. The first part of the trial consists of presentation of the first two terms of the analogy; the second part consists of full presentation. The fourth subtask involves a very small subset of the full task in the second part of the trial. The first part of the trial consists of presentation of the first three terms of the analogy; the second part consists of full presentation, but requires processing of only the last two terms.

The task decomposition described above serves to separate components of information processing that would be confounded if only the full task were presented. In order to see why, one must first know something about the proposed theory of analogical reasoning (Sternberg, 1977a, 1977b). According to the theory, solution of an analogy requires (a) <u>encoding</u> of each term of the analogy, (b) <u>inference</u> of the relation between the first two terms of the analogy ("Four score and seven years ago" is a quotation from Lincoln), (c) <u>mapping</u> of the relation between the first and third terms of the analogy ("Four score and seven years ago" and "I'm not a crook" are both quotations), (d) <u>application</u> of the relation from the third term to the answer options ("I'm not a crook" is a quotation from Nixon, not Capone), and (e) <u>response</u> (the correct answer is "a"). Optionally, a sixth <u>justification</u> process may be used to justify one option as superior when none seem to be exactly correct. Suppose only the full task were presented to subjects. Then according to certain information-processing models of analogical reasoning (which cannot be described here for lack of space) under the general theory, (a) encoding and response would be confounded, since response is constant across all analogy types (one response is always required), and encoding is also constant across all analogy types (five analogy terms always need to be encoded); (b) inference and application would be confounded, since the relation between the third term and the correct option is always the same as that between the first two terms. But precueing permits disentanglement of components by selective dropout of components required for processing. By varying the amount of encoding required for the various subtasks, the method of precueing permits separation of encoding from the constant response. And by eliminating the inference component from the third and fourth subtasks (while retaining the application component), it becomes possible to distinguish inference from application. Recall that in these two subtasks, the first two terms of the analogy were presented during precueing, so that inference could be completed before the full analogy was presented.

The precueing method obviously assumes additivity across subtasks. Two methods of testing additivity have been proposed (Sternberg, 1977b), although they can only be briefly mentioned here. The first requires testing of interval scores for simplicial structure. The second involves comparison of parameter estimates for the uncued condition alone with those for all the conditions combined. The data from three experiments on analogical reasoning showed reasonable conformity to the assumption of additivity. More importantly, even when the assumption of additivity was violated to some degree, the method of precueing proved to be robust, yielding sensible and informative data nevertheless. The method was quite successful in its application to analogy problems. The best model under the theory of analogical reasoning accounted for 92%, 86%, and 80% of the variance in the latency data for experiments using People Piece (schematic-picture), verbal, and geometric analogies.

Linear syllogisms. The method of precueing has also been applied in two experiments on linear syllogisms, or three-term series problems (Sternberg, Note 1). In the first experiment, subjects were presented with problems such as "John is taller than Pete. Pete is taller than Bill. Who is tallest? John Pete Bill." Order of names was counterbalanced. Trials again occurred in two parts. In the first part, subjects received either a blank field or the two premises of the problem. (A third condition, involving presentation of only the first premise, might have been used, but wasn't.) In the second part, subjects received the whole problem. In each trial, subjects indicated when they were ready to receive the whole item, and then indicated as their response one of the three terms of the problem. A possible limitation of this manner of presentation is that it seems to force serial ordered processing, whereas when left to their own devices, subjects might process the problems differently, for example, by reading the question first. A second experiment was therefore done.

In the second experiment, the same type of problem was used, except that the question was presented first: "Who is tallest? John is taller than Pete. Pete is taller than Bill. John Pete Bill." Again, order of names was counterbalanced. There were three precueing conditions. In the first, a blank field was presented during the first part of the trial. In the second, only the question was presented during the first part of the trial. In the third, the question and the premises were presented in the first part of the trial, so that subjects needed in the second part of the trial to discover only the ordering of the answer options. The full problem was always presented in the second part of the trial.

The methodology was again quite successful. The best model, my own mixed model (Sternberg, Note 1), accounted for 98% of the variance in the latency data from the first experiment, and 97% of the variance in the latency data from the second experiment. In these experiments (but not in the analogy experiments), model fits were substantially lower in the conditions comprising the full problems only: 81% and 74%. Worth noting, however, is that the reliabilities of these subsets of the latency data were only .86 and .82, meaning that even here most of the reliable variance was accounted for. The higher fits of the models to data with precueing were due to disentanglement of encoding from response. When only full problems are presented, it is impossible to separate premise encoding time from response time, since both are constant over problem types: There are always two premises and one response. Separation of the encoding component substantially increased the variance in the latency data, and hence the values of R^2.

Other problem types. The method of precueing has also been applied in the presentation of classification, series completion, and topology problems. In the classification problems, subjects were presented with two groups of two items each, and a target item. The subjects had to indicate in which group the target belonged. For example, one group might be "(a) robin, sparrow," the other "(b) haddock, flounder." If the target were "bluejay," the correct answer would be (a). Precueing was accomplished by presenting either a blank field in the first part of the trial, or just the two groups of items. Further precueing might have been accomplished by presenting just one group of items in the first part of the trial, although this was not in fact done.

In the series completion problems, subjects were presented with a linear ordering that they then had to complete, for example, "infant, child, adolescent, (a) adult, (b) teenager." Precueing was accomplished by presenting either a blank field or just the first three terms of the item in the first part of the trial.

In the topology problems, the subject was presented with a picture of a dot embedded in a complex geometric drawing. The subject was also presented with two other geometric drawings, neither of which contained a dot. The subject had to indicate in which of the two drawings at the right a dot could be placed so that it met the same constraints as the dot at the left. For example, if the dot at the left was inside a square, outside a circle, and below a line, then the subject had to choose the single drawing at the right in which a dot could be placed that met the same constraints. Precueing was accomplished by presenting either a blank field or just the picture with the dot in the first part of the trial.

Data from seven experiments using these three types of items with differing kinds of content (schematic-picture, verbal, geometric for classifications and series completions; geometric only for topologies) have not yet been fully analyzed. Preliminary indications, however, are that the method of precueing was successful in each case.

Evaluation of method. The method of precueing has both positive and negative aspects associated with it. On the positive side, (a) it permits disentanglement of components that otherwise would be confounded; (b) by doing so, it permits comparison of models that otherwise would be indistinguishable; (c) it increases the number of data points to be modeled, thereby helping to guard against the spurious good fit that can result when relatively large numbers of parameters are estimated for relatively small numbers of observations; (d) it requires the investigator to specify in what interval(s) of processing each mental operation takes place, thereby forcing the investigator to explicate his or her model in considerable detail; (e) it provides scores for performance in a series of nested processing intervals, rather than merely for the total task. On the negative side, (a) the method requires at least a semblance of additivity across subtasks; (b) it requires use of tachistoscopic or computer equipment to present each trial; (c) it requires individual testing; (d) it is not suitable for young children because of its complexity. In the uses to which the method has been put so far, the advantages of precueing have clearly more than offset its limitations.

New Methods of Task Decomposition

During the past two years, I have extended componential methodology by using new methods of task decomposition. I will describe these methods in the present section.

Method of Partial Tasks

In the method of partial tasks, complete items are presented involving either a full set of hypothesized components or just some subset of these components. The method differs from the method of precueing in that trials are not split into two parts. Decomposition is effected with unitary trials. The partial and full tasks, however, are assumed to be additively related, as in the method of precueing.

Linear syllogisms. The method of partial tasks has been used in four experiments on linear syllogisms (Sternberg, Note 1, Note 2). The full task consisted of the standard linear syllogism (three-term series) problem as described earlier. The partial task consisted of a two-term series problem, for example, "John is taller than Pete. Who is tallest?" (The ungrammatical superlative was used in the question to preserve uniformity with the three-term series problems.) The mixed model of linear syllogistic reasoning specified the component processes involved in both the two and three-term series problems, specifying the processes involved in the former as a subset of the processes involved in the latter. The values of R^2 were .97, .97, and .97 with all items considered, and .84, .88, and .84 with only three-term series items considered. Note that these values are quite similar to those obtained under the method of precueing. Values of parameters were also remarkably similar, with two exceptions (predicted, for reasons that cannot be described here, by the mixed model).

Categorical syllogisms. The method of partial tasks has also been applied in the investigation of categorical syllogisms (Sternberg & Turner, Note 3). The full task was a standard categorical syllogism, with premises like "All B are C. Some A are B." The subject was also presented with a conclusion, such as "All A are C," and had to indicate whether this conclusion was definitely true, possibly true, or never true of the premises. The partial task involved presentation of only a single premise, such as "Some A are B." The subject again had to decide whether a conclusion, such as "Some A are B," was definitely, possibly, or never true of the (in this case single) premise.

Whereas the primary dependent variable of interest in the previously described experiments was solution latency, the primary dependent variable in this experiment was response choice. The preferred model of syllogistic reasoning, the transitive-chain theory (Guyote & Sternberg, Note 4), accounted for 96% of the variance in the response-choice data from the full task, and 96% of the variance in the response-choice data from the partial task. Fits were not computed for the combined data, since in this particular experiment we happened to be interested in the full task as an "encoding plus combination task" and in the partial task as an "encoding only" task. These data indicate not only that the method of partial tasks can be applied successfully to categorical syllogisms, but that it can be applied to response-choice as well as latency data.

Evaluation of method. This method seems to share all of the advantages of the method of precueing, but only one of its disadvantages, namely, the assumption of additivity, in this case between the partial and the full task. The method of partial tasks therefore seems to be the preferred method when one has the option of using either of the two methods. Two additional points need to be considered, however. First, additivity may be obtained across precueing conditions but not from partial to full tasks, or vice versa. Thus, some amount of pilot testing may be needed to determine which method is more likely to yield additivity across conditions.

Second, some tasks are decomposable by either method, but others may be decomposable only by one or the other method. I have found the method of precueing applicable to more tasks than the method of partial tasks, although the differential applicability may be a function of the particular tasks I have investigated. In any case, the decision of which method to use can be made only after a careful consideration of task demands and decomposability. In some cases, the investigator may choose to use both methods, as in Sternberg (Note 1).

Method of Stem-Splitting

Analogies. The method of stem-splitting involves items requiring the same number of information-processing components, but different numbers of executions of the various components. It combines features of the method of precueing with those of the method of partial tasks. So far, the method has been applied only to verbal analogies. Using the method of stem-splitting, we presented verbal analogies in three different formats (Sternberg & Nigro, Note 5):

1. red : blood :: white : (a) color
   (b) snow

2. red : blood :: (a) white : snow
   (b) brown : color

3. red : (a) blood :: white : snow
   (b) brick :: brown : color

The number of answer options was allowed to vary from two to four for individual items. Consider how the different item types involve different numbers of executions of the same components. The first item requires encoding of five terms, inference of one relation, mapping of one relation, application of two relations, and one response. The second item requires encoding of six terms, inference of one relation, mapping of two relations, application of two relations, and one response. The third item requires encoding of seven terms, inference of two relations, mapping of two relations, application of two relations, and one response. (In each case, exhaustive processing of the item is assumed.) Varying the number of answer options also creates further variance in the numbers of operations required.

This method has been used with children as young as the third grade level and as old as the college level. The data from the experiment have not yet been fully analyzed, although preliminary indications are most encouraging. Even the youngest children understood the task, and performed at a level well above chance. Indications are that we will be able to account for over 80% of the variance in the data at the higher (ninth grade and adult) levels, and possibly for as much of the variance in the data for the younger levels as well.

Evaluation of method. This method has barely been tried, and so I am not yet in a position to evaluate fully its usefulness. On the positive side, (a) it could be (although has not yet been) used for group testing in conjunction with booklets of the kind described in the next section, (b) it requires no special equipment to administer items, (c) it is feasible with young children, and (d) it seems to create a certain added interest to the problems for the subjects. On the negative side, (a) the success of the method has not yet been adequately demonstrated, (b) the generality of the method to problems other than analogies has not yet been shown, and (c) the method seems more likely than the preceding ones to generate special strategies that are inapplicable to standard (complete) tasks.

Method of Systematically Varied Booklets

Analogies. In previous methods, the unit of presentation was the single item. In this method, the unit of presentation is the booklet. In previous methods, subjects were given as long as they needed to complete each individual item. In this method, subjects are given a fixed amount of time to complete as many items as they can within a given booklet. The number of items in the booklet should exceed the number of items that subjects can reasonably be expected to complete in the given time period. The key to the method is that all items within a given booklet are homogeneous with respect to the theory or theories being tested. Although the same items are not repeated, each item serves as a replication with respect to the sources of difficulty specified by the theory. Although items within a given booklet are homogeneous, items are heterogeneous across booklets. In this method, specifications of the items within a booklet are varied in the same way that specifications of single items are varied in the preceding methods.

The method of systematically varied booklets has been employed only with two types of schematic-picture analogies (Sternberg & Rifkin, Note 6). In the two experiments done so far, the method has been used successfully with children as young as grade 2 and as old as college age. Subjects at each grade level were given 64 seconds in which to solve the 16 analogies contained in each booklet. Independent variables were numbers of schematic features changed between the first and second analogy terms, first and third analogy terms, and the first and second analogy answer options. Items within a given booklet were identical in each of these respects. Three dependent variables were derived from the raw data. The first was latency for correctly answered items, obtained by dividing 64 by the number of items correctly completed. This measure takes into account both quality and quantity of performance. The second dependent variable was latency for all answered items, obtained by dividing 64 by the number of items completed, whether they were completed correctly or incorrectly. This measure takes into account only quantity of performance. The third dependent variable was error rate, obtained by dividing the number of items answered at all. This measure takes into account only quality of performance.

In a first experiment, model fits (R^2) for the best model were .91, .95, .90, and .94 for latencies of correct responses at grades 2, 4, 6, and college; they were .87, .94, .93, and .94 for latencies of all responses at each grade level; and they were .26, .86, .52, and .65 for error rates at each level. The fits for errors, although lower than for the latencies, were almost at the same levels as the reliabilities of each of the sets of data, indicating that only slightly better fits could possibly have been obtained. Model fits in a second experiment were slightly lower than in the first experiment, but so were the reliabilities of the data.

Evaluation of method. The method of systematically varied booklets has three distinct advantages and two distinct disadvantages. Its advantages are that (a) it is practical even with very young children, (b) it requires no special equipment for test administration, and (c) it is adopted to group testing. Its disadvantages are that (a) it is not possible to obtain a pure measure of time spent only on items answered correctly (or incorrectly), since times are recorded only for booklets, not for individual items, and that (b) the method is not particularly well suited to disentangling components. In some of the models tested, for example, encoding and response, and inference and application, were confounded.

Method of Complete Tasks (Standard Method of Presentation)

The method of complete tasks is simply the standard method of presenting only the complete item. It is suited to items in which no confoundings of components occur.

Categorical syllogisms. The method of complete tasks was used in the presentation of categorical syllogisms (Guyote & Sternberg, Note 4). In a first experiment, subjects were presented with syllogistic premises, such as "All B are C. All A are B," plus a set of four possible conclusions (called A, E, I, and O in the literature on syllogistic reasoning), "All A are C. No A are C. Some A are C. Some A are not C." plus the further conclusion, "None of the above." Subjects had to choose the preferred conclusion from among the five. In a second experiment, concrete rather than abstract terms were used. Premises were either factual (No cottages are skyscrapers), counterfactual (No milk cartons are containers), or anomalous (No headphones are planets). In a third experiment, the quantifiers "most" and "few" were used instead of "some." In a fourth experiment, premises were presented in the form "All A are B. X is an A," and subjects were asked simply to judge whether a conclusion such as "X is a B" was valid or invalid. Our transitive-chain model outperformed the other models of response choice to which it was compared, yielding values of R^2 of .97 for abstract content, .91 for concrete factual content, .92 for concrete counterfactual content, .89 for concrete anomalous content, .94 when "most" and "few" were substituted for "some," and .97 for the simpler syllogisms requiring only a valid-invalid judgment. Latency models were also fit to some of the data, with excellent results.

One of the assumptions of the preferred transitive-chain model is that encoding is flawless: Errors are hypothesized to be made in other stages of syllogistic reasoning. Modeling of the data via the method of complete tasks does not permit a direct test of this assumption. The method of partial tasks did permit such a test, however, and the Sternberg-Turner (Note 3) data described earlier provided support for this assumption when encoding was separated from subsequent stages of reasoning.

Conditional syllogisms. The method of complete tasks was also used in testing the transitive-chain model on conditional syllogisms of the form "If A then B. A. Therefore, B." The subject's task was to evaluate the conclusion as either valid or invalid. The model accounted for 95% of the variance in the response-choice data.

Evaluation of method. The main advantages of this method are that (a) it is the simplest of the methods described, and (b) it does not require any assumptions about additivity across conditions of decomposition. The main disadvantage of the method is that in many if not most tasks, information-processing components will be confounded. These confoundings can lead to serious consequences, as discussed in Sternberg (1977b). The method is the method of choice only when it is possible for it to disentangle all component processes of interest.

Conclusions

The primary purpose of this article was to show the generalizability of the procedures of componential analysis to tasks beyond the analogies tasks to which the method was originally applied (Sternberg, 1977a, 1977b).

In the course of demonstrating the generalizability of the method, some new procedures for task decomposition were briefly noted and explicated. The focus in these explications was on the experimental procedures used, rather than on the substantive theories tested or the quantification of these theories. Substantive and quantitative details can be found in the original articles. The data for a rather wide variety of reasoning tasks indicate that componential analysis is indeed applicable to tasks with varying degrees of resemblance to analogies, ranging from tasks that are quite similar (for example, series completions) to tasks that are quite different (for example, categorical syllogisms).

It was not possible in this particular article to demonstrate the range of advantages that accrued from componential decomposition of tasks, and from the full set of procedures involving intensive and extensive task analysis, and internal and external validation of given tasks. But my collaborators and I believe that the full set of procedures has rewarded us with insights that seem not to be available through standard differential and information-processing methods of model testing. We therefore believe that componential analysis merits further exploration both in laboratory and practical settings. We like to visualize the day in the future when it might be possible to construct tests of intelligence that derive from rational componential theories of abilities, rather than from procedures that while empirically sound, may be theoretically vacuous.

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Footnote

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